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Naturally light sterile neutrinos in gauge mediated supersymmetry breaking

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Abstract: Moduli are generic in string (M) theory. In a large class of gauge-mediated Supersymmetry breaking models, the fermionic components of such fields have very light masses, around the eV scale, and non-negligible mixing with active neutrinos, of order 10^{-4}. Consequently, these fermions could play the role of sterile neutrinos to which active neutrinos oscillate, thus affecting measurements of solar neutrinos or of atmospheric neutrinos. They could also provide warm dark matter, thus affecting structure formation.

Keywords: Neutrino Physics, Supersymmetric Standard Model, Solar and Atmospheric Neutrinos.

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Contents

1. Introduction

Light sterile neutrinos are occasionally invoked by theorists to explain various hints of neutrino masses which cannot be accommodated in a framework of only three light active neutrinos (see *e.g.* refs. [1]–[28]). There are, however, three puzzles related to the hypothesis that light sterile neutrinos may play a role in various observations:

(i) The Majorana mass term of a sterile neutrino is not protected by any Standard Model (SM) gauge symmetry and can, therefore, be arbitrarily large. The mass that is relevant to the various experiments is at or below the eV scale.

(ii) The Dirac mass term that mixes a sterile neutrino with an active one is protected by the electroweak breaking scale and is expected to be in the range $m_e - m_Z$. To explain any of the experimental results we need this term to be at or below the eV scale.

(iii) The two scales described above are in general independent of each other. Yet, the mixing between the sterile and the active neutrino, which is given by the ratio of the two scales, cannot be much smaller than $\mathcal{O}(10^{-2})$ and, for some purposes, needs to be of $\mathcal{O}(1)$. Then some mechanism that relates the two scales seems to be required.

Many models were proposed that give sterile neutrinos with the required features. Most existing models employ a rather ad-hoc symmetry structure (or just give an ansatz) to induce the relevant parameters. The case for light sterile neutrinos would become much stronger if some well-motivated extension of the SM *predicted* their existence. We argue that in models of Gauge Mediated Supersymmetry Breaking (GMSB), the fermionic components ψ_N of any SM singlet superfield N that it massless in the Supersymmetry limit and, in particular, the moduli fields, are generically expected to have masses and mixing that could be relevant to various experimental and observational results.

2. Light singlet fermions in supersymmetric models

We assume that the dominant source of supersymmetry breaking is an F term of a chiral superfield S: $F_S \neq 0$. Mass terms involving ψ_N arise then from the Kahler potential and involve supersymmetry breaking. The leading contribution to the mass term $m_{NN}\psi_N\psi_N$ is of the form

$$\frac{(S^\dagger)_{\bar\theta\bar\theta}(NN)_{\theta\theta}}{m_{\rm Pl}} \implies m_{NN} \sim \frac{F_S}{m_{\rm Pl}}\,. \tag{2.1}$$

The singlet N field can mix with a lepton doublet field L. The leading contribution to the mass term $m_{LN}\psi_L\psi_N$ is of the form

$$\frac{(\phi_d^\dagger)_{\bar\theta\bar\theta}(LN)_{\theta\theta}}{m_{\rm Pl}} \implies m_{LN} \sim \frac{\mu\phi_u}{m_{\rm Pl}}\,. \tag{2.2}$$

Here, $\phi_{d,u}$ are the two Higgs fields of the MSSM and we used the fact that the $\mu\phi_u\phi_d$ term in the superpotential leads to $F_{\phi_d} \sim \mu\phi_u$. The mass terms m_{NN} and m_{LN} determine the two physically relevant quantities, that is the mass of ψ_N, $m_N \sim m_{NN}$, and its mixing with active neutrinos, $s_{LN} \sim m_{LN}/m_{NN}$.[1]

Note that the contribution from F_{ϕ_d} to m_{LN} is crucial for ψ_N to be relevant to neutrino physics. The reason is that m_{LN} breaks both supersymmetry and the electroweak symmetry. Without F-terms of $SU(2)_L$ non-singlets, there would be a separate suppression factor for each of the two breakings, making m_{LN} too small for our purposes. Explicitly, if the only F term to play a role were F_S, then we would get $m_{LN} \sim \frac{F_S\phi_u}{m_{\rm Pl}^2}$ and consequently $s_{LN} \sim \frac{\phi_u}{m_{\rm Pl}} \sim 10^{-16}$, independent of the mechanism that mediates supersymmetry breaking. Such mixing is too small to affect any neutrino experiment. In contrast, the contribution to m_{LN} from F_{ϕ_d} leads to a value for s_{LN} that is model dependent and that can be sizable. Assuming that μ is of the order of the electroweak breaking scale, we get

$$m_{LN} \sim \frac{m_Z^2}{m_{\rm Pl}} \sim 10^{-5}\ eV\,. \tag{2.3}$$

The scale of F_S (and, consequently, the values of m_N and s_{LN}) depends on the mechanism that communicates SUSY breaking to the observable sector. In supergravity

[1]We implicitly assume here that the mass and mixing of ψ_N are described effectively by a 2×2 matrix, and that $m_{LL} \lesssim m_{NN}$.

models, where $F_S \sim m_Z m_{\rm Pl}$, we get

$$m_N \sim m_Z \sim 10^2 \ GeV, \quad s_{LN} \sim \frac{m_Z}{m_{\rm Pl}} \sim 10^{-16} \,. \tag{2.4}$$

Then ψ_N is practically decoupled from the observable sector and does not have any observable signatures.

In GMSB models [29]–[31] we have a more interesting situation. There, $F_S \sim Cm_Z^2/\alpha^2$, where $C \gtrsim 1$ depends on the details of the model (for a review, see [32]). We now get

$$m_N \sim \frac{Cm_Z^2}{\alpha^2 m_{\rm Pl}} \sim 0.1 \ eV \ C \,, \quad s_{LN} \sim \frac{\alpha^2}{C} \sim \frac{10^{-4}}{C} \,. \tag{2.5}$$

The mass scale for ψ_N is not far from those relevant to galaxy formation ($\sim 10 \ eV$), atmospheric neutrinos ($\sim 0.1 \ eV$) and solar neutrinos ($\sim 10^{-3} \ eV$). The mixing is small but non-negligible. We conclude then that in GMSB models, the fermionic fields in the moduli can, in principle, play the role of sterile neutrinos that are relevant to various observations.

We emphasize that eq. (2.5) gives only naive order of magnitude estimates. Each of its relations might be somewhat modified by unknown coefficients, expected to be of $\mathcal{O}(1)$. Furthermore, there might be other ingredients in the model that affect even the order of magnitude estimates. In the next section we show how simple variations within our basic framework might bring the mass and the mixing of ψ_N closer to those required to explain the various experimental results.

Before concluding this section, we would like to mention some related previous works. A supergravity scenario where the fermionic fields in the moduli play the role of sterile neutrions was proposed in ref. [13]. This was done, however, with a special ansatz for the supersymmetry breaking mass terms. Neutrino masses in the GMSB framework were recently discussed in ref. [33]. Their model, however, has no sterile neutrinos and involves R parity violation. Reference [18] has discussed the possibility that modulinos play the role of sterile neutrinos in GMSB models. In particular, the fact that the mass scale for m_{NN} is naturally in the relevant range (eq. (2.1)) was realized in [18]. However, the contribution to m_{LN} from F_{ϕ_d} (eq. (2.2)) was missed and bilinear R_p violating terms were invoked instead.

3. Solar and atmospheric neutrinos

Simple variations on the naive estimates given above could make the sterile neutrino parameters consistent with solutions to the solar neutrino problem [34] or to the atmospheric neutrino problem [35].

Let us consider first the possibility that the relevant superfields N transform under some approximate symmetry. This could be a horizontal symmetry invoked to explain the smallness and hierarchy in the flavor parameters. Take, for example, a $U(1)$ symmetry broken by a small parameter λ, to which we attribute charge -1. Take N and

L to carry charges p and q, respectively, under the symmetry. Then, (2.5) is modified:

$$m_{NN} \sim \frac{\lambda^{2p} C m_Z^2}{\alpha^2 m_{\rm Pl}} \sim \lambda^{2p} C \times 0.1\ eV\,, m_{LN} \sim \frac{\lambda^{p+q} m_Z^2}{m_{\rm Pl}} \sim \lambda^{p+q} \times 10^{-5}\ eV\,,$$
$$s_{LN} \sim \frac{\alpha^2}{\lambda^{p-q} C} \sim \frac{10^{-4}}{\lambda^{p-q} C}\,. \tag{3.1}$$

To get $s_{LN} = \mathcal{O}(1)$, we would need $m_{NN} \lesssim 10^{-5}\ eV$, so that ψ_N is unlikely (in this simple scenario) to play a role in the atmospheric neutrino anomaly or in the large angle MSW solution to the solar neutrino problem. On the other hand, two relevant sets of parameters can be easily produced by the approximate symmetry:

(I) Take $C \sim 1$, $\lambda^p \sim 0.1$, and $q = 0$:

$$m_{NN} \sim 10^{-3}\ eV\,, \quad m_{LN} \sim 10^{-6}\ eV\,, \quad s_{LN} \sim 10^{-3}\,. \tag{3.2}$$

This is not far from the small angle MSW solution to the solar neutrino problem. (The mixing angle is somewhat small but, as mentioned above, could be modified by the unknown coefficients of $\mathcal{O}(1)$.)

(II) Take $C \sim 1$, $\lambda^p \sim 10^{-2}$, and $q = -p$:

$$m_{NN} \sim 10^{-5}\ eV\,, \quad m_{LN} \sim 10^{-5}\ eV\,, \quad s_{LN} \sim 1\,. \tag{3.3}$$

This set of parameters is appropriate for the vacuum oscillation solution to the solar neutrino problem.

Another variation on the naive estimates arises if the relevant heavy scale (call it $m_{\rm NP}$ for New Physics) in the nonrenormalizable terms is lower than $m_{\rm Pl}$. Then both m_{NN} and m_{LN} will be enhnaced compared to (2.1) and (2.2). A particularly intriguing option is that the string scale identifies with the scale of gauge unification [36], that is $m_{\rm NP} \sim 10^{16}\ GeV$. This leads to our third example:

(III) Take $m_{\rm NP} \sim 10^{16}\ GeV$, $C \sim 1$, $\lambda^p \sim 10^{-2}$, and $q = -p$:

$$m_{NN} \sim 10^{-3}\ eV\,, \quad m_{LN} \sim 10^{-3}\ eV\,, \quad s_{LN} \sim 1\,. \tag{3.4}$$

These parameters give the large angle MSW solution to the solar neutrino problem.

Either a surprisingly small $m_{\rm NP}$ or a surprisingly large $\mu\phi_d$ may make ψ_N relevant to the atmospheric neutrino problem. First, an even lower cut-off scale, $m_{\rm NP} \sim 10^{14}\ GeV$, would give $m_{LN} = \mathcal{O}(0.1\ eV)$. However, there is no particularly attractive scenario that requires such a scale for $m_{\rm NP}$. Second, a large μ [37] could also lead to a large m_{LN}. Note, however, that in order to prevent a negative mass-squared for the stop, one needs $m_{\tilde t}^2 \geq \mu\phi_d$. In this scenario we have then an interesting relation between the stop sector and the neutrino sector: the mixing between the sterile and the active neutrinos is bounded by $m_{\tilde t}^2/m_{\rm Pl}$.

(IV) Take $m_{\rm NP} \sim 10^{14}\ GeV$, $C \sim 1$, $\lambda^p \sim 10^{-2}$, and $q = -p$, or $\mu \sim \sqrt{F_S}$, $C \sim 10^4$, $\lambda^p \sim 10^{-2}$, and $q = -p$. Then

$$m_{NN} \sim 10^{-1}\ eV\,, \quad m_{LN} \sim 10^{-1}\ eV\,, \quad s_{LN} \sim 1\,, \tag{3.5}$$

which can solve the atmospheric neutrino problem.

4. Nucleosynthesis and galaxy formation

The number of light neutrinos ($m_\nu \lesssim 1\ MeV$) that were in equilibrium at the neutrino decoupling temperature ($T_{\rm dec} \sim$ a few MeV), $N_\nu^{\rm eff}$, cannot be much larger than three. Otherwise, the consistency between the predictions of the standard model of Big Bang Nucleosynthesis (BBN) and the observed abundance of primordial light elements will be lost. A sterile neutrino that mixes with the active ones contributes to $N_\nu^{\rm eff}$ because neutrino oscillations can bring it into equilibrium above $T_{\rm dec}$. Consequently, one can use the BBN constraints to exclude regions in the $\Delta m^2_{4i} - \sin^2 2\theta_{4i}$ plane [38]–[43]. (Here ν_4 is the light mass eigenstate with a dominant ν_s component.) In our framework, $\Delta m^2_{4i} = \mathcal{O}(m_N^2)$ and $\sin^2 2\theta_{4i} = \mathcal{O}(4s^2_{LN})$. The calculation of the bounds is quite complicated. An approximate analytical constraint is given in [40], $\Delta m^2_{4i} \sin^4 2\theta_{4i} \lesssim 5 \times 10^{-6}\ eV^2$, corresponding to $N_\nu^{\rm eff} \leq 3.4$. This leads to

$$m_N s^2_{LN} \lesssim 5 \times 10^{-4}\ eV\,. \tag{4.1}$$

The naive estimates of eq. (2.5) yield $m_N s^2_{LN} \sim 10^{-9}\ eV/C$, which is well below the bound (4.1). Note, however, that (4.1) is very sensitive to s_{LN}. Taking into account the various variations discussed in the previous section, we find that (4.1) leads to

$$\frac{\lambda^{2q}}{C}\frac{m_{\rm Pl}}{m_{\rm NP}} \lesssim 5 \times 10^5\,. \tag{4.2}$$

This bound is fulfilled for the small angle MSW (3.2) and the vacuum oscillation (3.3) solutions of the solar neutrino problem but (as is well known) violated if ψ_N plays a role in the large angle MSW solution of the solar neutrino problem (3.4) or, in particular, in the atmospheric neutrino anomaly (3.5).[2]

A sterile neutrino could also provide a significant warm dark matter component (see e.g. [47]). To have $\Omega_{\psi_N} = \mathcal{O}(1)$ requires

$$m_N s_{LN} \sim 0.1\ eV\,, \quad 10\ eV \lesssim m_N \lesssim 1\ keV\,. \tag{4.3}$$

A particulary plausible framework where (4.3) is realized is that of GMSB models with $C \sim 10^4$, which gives:

$$F_S \sim 10^{12}\ GeV^2 \quad \Longrightarrow \quad m_{LN} \sim 0.1\ eV\,, \quad m_N \sim 1\ keV\,. \tag{4.4}$$

5. Intermediate scale gauge mediated supersymmetry breaking

All the examples that we discussed above require that the scale of supersymmetry breaking is low, $\sqrt{F_S} \sim 10^4 - 10^6\ GeV$. We now discuss another class of GMSB

[2] The constraint (4.1) could be evaded if there had been a large lepton asymmetry in the early Universe [44]–[46]. The constraint could also be relaxed if the bound on $N_\nu^{\rm eff}$ is weaker than the one we quoted.

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models, where ψ_N can play the role of a sterile neutrino if the supersymmetry breaking scale is much higher, $\sqrt{F_S} \sim 10^6 - 10^9\ GeV$.

Consider the case where S, which is responsible for Supersymmetry breaking, transforms under some $U(1)$ symmetry [48]. Assume that N is neutral under this symmetry. Then the contribution (2.1) to m_{NN} is forbidden. Instead, the leading contribution is of the form

$$\frac{(S^\dagger)_{\bar\theta\bar\theta}(S)_1(NN)_{\theta\theta}}{m_{\rm Pl}^2} \quad\Longrightarrow\quad m_{NN} \sim \frac{\Lambda S^2}{m_{\rm Pl}^2}\,. \tag{5.1}$$

Here Λ is the dimensionful parameter that sets the scale for the masses of the MSSM particles in GMSB models ($m_{\lambda_i} \sim \frac{\alpha_i}{4\pi}\Lambda$):

$$\Lambda \equiv \frac{F_S}{S} \sim 10^4 - 10^6\ GeV\,. \tag{5.2}$$

Assuming that ϕ_d, ϕ_u and L are also neutral under the $U(1)$ symmetry (or that they carry appropriate charges), the estimate of m_{LN} in eq. (2.2) remains valid.

Unlike our discussion above, where $F_S \gg \mu\phi_u$ led us to expect that $m_{NN} > m_{LN}$, we now have to distinguish between two cases, depending on the value of

$$C' = \left(\frac{\Lambda}{10^6\ GeV}\right)\left(\frac{S}{10^8\ GeV}\right)^2. \tag{5.3}$$

The point is that $m_{NN}/m_{LN} \sim C'$. For $m_{NN} \gtrsim m_{LN}$, we get,

$$m_N \sim C'\ 10^{-5}\ eV\,, \quad s_{LN} \sim 1/C'\,, \quad (C' \gtrsim 1)\,. \tag{5.4}$$

But for $m_{NN} \ll m_{LN}$ (and assuming, as before, that $m_{LL} \lesssim m_{NN}$) the situation is drastically different: the active and the sterile neutrino form a pseudo-Dirac neutrino of mass m_{LN} and small splitting m_{NN}:

$$\begin{aligned} m_N &\simeq\ m_L \sim 10^{-5}\ eV, \quad \frac{m_N - m_L}{m_N + m_L} \sim C'\,, \\ s_{LN} &\simeq\ \sqrt{2}/2\,, \quad (C' \ll 1)\,. \end{aligned} \tag{5.5}$$

Again, ψ_N could play a role in the various neutrino experiments. Here are a few examples:

(I) $C' \sim 10^2$ corresponds to the small angle MSW solution to the solar neutrino problem.

(II) $C' \lesssim 1$ corresponds to the vacuum oscillation solution to the solar neutrino problem.

(III) $m_{\rm NP} \sim 10^{16}\ GeV$ and $C' \lesssim 10^{-2}$ correspond to the large angle MSW solution to the solar neutrino problem.

(IV) $m_{\rm NP} \sim 10^{14}\ GeV$ and $C' \lesssim 10^{-4}$ can explain the atmospheric neutrino results.

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Note that, in order that ψ_N will be relevant to our purposes, we need C' that is not much larger than 1. This is important since a too large C' leads to phenomenological problems:

a. For $S \gtrsim 10^{15}\ GeV$, the non-universal supergravity contributions to sfermion masses become comparable to the universal gauge-mediated contributions. Consequently, the supersymmetric flavor problem is no longer solved [49].

b. For $S \gtrsim 10^{10}\ GeV$, the S-scalar decays late and its hadronic decay products overproduce light nuclei. Consequently, the successful predictions of the standard BBN no longer hold [48].

We would like to emphasize two attractive points about sterile neutrinos in the framework of intermediate-scale GMSB models discussed in this section (compared to the GMSB models of section 2). First, for models with $m_{NN} \sim F_S/m_{\rm Pl}$ to give ψ_N's that are relevant to neutrino physics, a rather low F_S is required ($F_S \lesssim 10^{12}\ GeV^2$). Direct experimental searches for diphoton events with large missing transverse energy [50]–[52] exclude large regions in the parameter space where the scale of F_S is low. Second, in many GMSB models of direct gauge mediation [32] the scale of F_S cannot be low.

6. Conclusions

If low-energy supersymmetry is a result of a high-energy string theory, then we expect quite generically that there exist singlet fields N that are massless in the supersymmetric limit (moduli). Our main point is very simple: for two large classes of gauge mediated supersymmetry breaking models, the supersymmtry-breaking masses of the fermionic fields ψ_N is around the eV scale and their mixing with active neutrinos is non-negligible. (In the first class, supersymmetry is broken at a scale $F_S \sim 10^8 - 10^{12}\ GeV^2$ and a term $S^\dagger NN$ in the Kahler potential is allowed. In the second class, $F_S \sim 10^{13} - 10^{17}\ GeV^2$ and $S^\dagger NN$ is forbidden.) Consequently, such fields could play the role of sterile neutrinos to which ν_e (ν_μ) oscillate, thus solving the solar (atmospheric) neutrino problem. They could also provide a warm component to the dark matter, thus affecting galaxy formation.

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